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Sensitivity Analysis for I-129 Wastes: Effect of Hydraulic Conductivity

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Abstract

Solid low-level radioactive wastes at the Savannah River Site (SRS) are disposed in trenches. In order to determine the permissible radioactive inventory limits for such disposal facilities, it is required to assess the behavior of radioactive waste material over long periods of time. The sensitivity of flow and I-129 (and similar radionuclides) transport in groundwater in the vadose zone to the hydraulic conductivities of the vadose zone subregions and the low-level waste is identified and quantified.

A trench configuration and simulation model have been developed to analyze the flow and transport of the radionuclide in the vadose zone as it migrates to the groundwater table. The analysis identifies and quantifies the major dependencies of the flow and radionuclide fractional flux on the subregion hydraulic conductivities. Analysis results indicate the importance of the hydraulic conductivity assigned to the materials modeled, thereby providing the modeler and decision makers with valuable insights on the potential impact of the hydraulic conductivity on flow and radionuclide transport.

1 Introduction

Disposal of radioactive material at the U.S. Department of Energy Savannah River Site (SRS), requires that the behavior of radioactive waste material be assessed over long periods of time in order to determine the permissible radioactive inventory limits for the disposal facility. This paper addresses the sensitivity of I-129 fluxes in groundwater in the vadose zone with respect to the hydraulic conductivities of the vadose zone and the low-level waste that has been disposed in trenches. The trench configuration and simulation model are based on the trench disposal model reported in Reference [1]. The simulation model allows one to analyze the flow and transport of the radionuclide in the vadose zone as it migrates to the groundwater table. The vadose zone transport results can be fed into a separate aquifer model (this is beyond the scope of this paper) to determine the maximum radionuclide concentration [2]. By using the simulation model, radionuclide sensitivity analyses are performed to:

(1) calculate flow velocities and fluxes of the radionuclide versus the hydraulic conductivities of the vadose zone and waste material.
(2) calculate the transport of the radionuclide in the vadose zone to the groundwater table.

The analysis results indicate the importance of the hydraulic conductivity assigned to the materials in the model, thereby providing valuable insight on the sensitivity of flow and transport to the hydraulic conductivities used.

2 Trench Configuration and Simulation Model

The trench configuration and flow model are based on the trench disposal model reported in Reference [1]. Trenches are below grade earthen disposal units with a 20 feet deep and 20 feet wide cross section. The waste has a nominal thickness of 16 feet and is covered by 4 feet of clean backfill.

The model domain consists of five subregions. The five subregions include:

1) Backfill above the waste
2) Upper waste zone
3) Lower waste zone
4) Upper vadose zone
5) Lower vadose zone

The trench is excavated solely through the upper vadose zone material. The base of the trench sits at the interface between the upper vadose zone and the lower vadose zone.

The flow analysis performed with the PORFLOW computer code [3] allows one to determine the steady-state flow field in the five subregions at multiple time periods that include the initial operational period (0-25 years), the institutional control period (25-125 years) with an interim cap placed at 25 years and maintained, and the third period (125-10,000 years) when dynamic compaction is applied at 125 years and a final cap is placed that is not maintained.

The following assumptions are made in the vadose zone flow model:

1) Waste settlement effects are neglected
2) The model considers only the vadose zone where the radionuclide flux that reaches the water table is determined.

The hydraulic conductivity K (in cm/sec) used in the governing equations of fluid and mass transport in the PORFLOW code is expressed as [3]:

$$K = k\rho g/\mu$$

where k = intrinsic permeability, cm^2
ρ = dry bulk density, g/cm^3
μ = dynamic viscosity, g/(cm sec)
g = gravitational acceleration, cm/sec^2

The transport analysis combines an initial waste inventory with multiple steady-state flow fields to determine the radionuclide flux at the water table. The simulation applies an inventory of 1 Ci of I-129. Subsequently, the predicted radionuclide concentration in the aquifer at a hypothetical 100m well can be compared to the Maximum Containment Level (MCL) allowed (1pCi/L) to calculate an inventory limit (this is beyond the scope of this paper). The results of the vadose zone analysis are radionuclide fluxes expressed in terms of Ci/yr per Ci of I-129 disposed. More details of the model description can be found in Reference [1].

3 Flow and Radionuclide Transport Analysis

The flow analysis consists of computing the flow velocity field in each subregion by using the PORFLOW code. By feeding the computed flow results into the PORFLOW transport model, the fractional flux of the radionuclide can be evaluated. The results presented were derived for the time interval 0-30 years when the radionuclide peak fractional flux occurs (based on earlier scoping analyses that considered the entire 10,000 years). Hydraulic conductivity data and other material properties used in the base case calculations are shown in Table 1.

Table 1 Key Conductivity, Density, and Porosity Parameters used in the Base Case of the Flow and Transport Analysis

Subregion	Horizontal Conductivity (cm/yr)	Vertical Conductivity (cm/yr)	Particle Density (g/cm^3)	Porosity (-)
Backfill	$3.8\ 10^3$	$3.8\ 10^3$	2.65	0.46
Upper Waste	$3.8\ 10^3$	$3.8\ 10^3$	2.65	0.46
Lower Waste	$3.8\ 10^3$	$3.8\ 10^3$	2.65	0.46
Upper Vadose	$2.0\ 10^3$	$2.7\ 10^2$	2.70	0.39
Lower Vadose	$1.0\ 10^4$	$2.9\ 10^3$	2.66	0.39

Water properties and infiltration data include:

Density: $0.9982\ g/cm^3$
Viscosity: $3.19\ 10^{-15}$ N-yr/cm^2
Reference Pressure: $10.13\ N/cm^2$
Infiltration Rate: 40 cm/yr

The flow and radionuclide fractional flux results obtained for the base case are:

Maximum horizontal velocity in waste, cm/yr: 28.69
Average vertical velocity in waste, cm/yr: 78.25
Peak fractional flux: $1.20\ 10^{-1}$

The sensitivity analysis consists of varying the hydraulic vertical or horizontal conductivity of a subregion (or group of subregions) to determine the effect on the flow field and the peak fractional flux. The sensitivity results are shown in Figure 1 and Table 2, and are analyzed below.

3.1 Variation of the Vertical Conductivity

Lower Vadose Zone (LVZ): [Fig. 1 (d)]:

As the vertical conductivity (Ky) of the lower vadose zone is reduced by a factor of 10, the vertical flow velocity in the waste is unchanged, and the horizontal velocity in the vadose zone is increased. The peak fractional flux is reduced from $1.20\ 10^{-1}$ to $1.09\ 10^{-1}$.

As the lower vadose zone vertical conductivity is increased by a factor of 100, the vertical flow velocity in the waste is unchanged and the horizontal velocity in the vadose zone is reduced. In this case, the peak fractional flux is increased to 1.35 10^{-1}.

Waste (W): [Fig. 1 (d)]:

As the waste vertical hydraulic conductivity is reduced by a factor of 10, the vertical flow velocity in the waste is decreased, resulting in a decrease in the peak fractional flux from 1.2 10^{-1} to 7.08 10^{-2}. Furthermore, as the conductivity of the waste is increased by a factor of 100, the flow velocity in the waste is increased, resulting in a peak fractional flux reduction from 1.20 10^{-1} to 1.09 10^{-1}. However, the peak fractional flux occurs sooner (8.8 years vs. 10 years). This result is due to the inventory of the waste that is depleted sooner and whose release is mostly controlled by the LVZ.

Upper Vadose Zone (UVZ): [Fig. 1 (e)]:

Reducing the vertical conductivity of the upper vadose zone by a factor of 5 results in an increase in the vertical velocity in the waste, and the peak fractional flux is increased from 1.20 10^{-1} to 1.33 10^{-1}. Furthermore, increasing the vertical conductivity of the upper vadose zone by a factor of 10 yields a significant decrease in the flow velocity in the waste, resulting in a reduction in peak fractional flux from 1.20 10^{-1} to 6.8 10^{-2}.

Backfill+W+UVZ: [Figs. 1(a) and 1(b)]:

Reducing the vertical conductivity of the backfill, waste, and upper vadose zone by a factor of 5 results in a decrease in vertical flow across the UVZ and a significant increase in the horizontal UVZ flow which in turn leads to an increase in both vertical and horizontal flows in the waste. As a result, the peak fractional flux increases from 1.20 10^{-1} to 1.27 10^{-1}.

If the vertical conductivities of the backfill, waste, and UVZ are increased by a factor of 5 and 100, both the vertical and horizontal velocities in the waste are reduced, resulting in a peak fractional flux reduced from 1.20 10^{-1} to 9.98 10^{-2}, and from 1.20 10^{-1} to 8.37 10^{-2}, respectively.

Backfill+W+UVZ+LVZ [Figs. 1(a) and 1(b)]:

Reducing the vertical conductivities of the backfill, waste, UVZ and LVZ by a factor of 5 results in a significant increase in the horizontal flow velocities in the BF, UVZ, and Waste, and an increase in vertical flow in the waste. As a result, the peak fractional flux increases from 1.20 10^{-1} to 1.26 10^{-1}.

If the vertical conductivities of the (BF+W+UVZ+LVZ) are increased by a factor of 5, both the vertical and horizontal velocities in the waste are reduced, resulting in a peak fractional flux equal to 8.59 10^{-2}. Furthermore, increasing the (BF+W+UVZ+LVZ) conductivities by a factor of 100, results in lower horizontal velocities and almost identical vertical velocities in the waste. In this case, the peak fractional flow is equal to 9.11 10^{-2}.

Backfill (BF) [Figs. 1(a) and 1(b)]:

Reducing the vertical conductivity of the backfill by a factor of 5 and 10 results only in small decreases in the flow velocity in the waste with a negligible effect on the peak fractional flux equal to 1.20 10^{-1}. This result is also valid for an increase of the backfill vertical conductivity by factors of 5 and 100. This result suggests that conductivity changes in the backfill have only a minimal impact on the peak fractional flux.

Backfill+W [Figs. 1(a) and 1(b)]:

Reducing the vertical conductivity of the backfill and the waste by factors of 5 and 10 results in a decrease in vertical flow velocity in the backfill and the waste zones. The horizontal velocity is also reduced. The net result is a decrease in the peak fractional flux from 1.20 10^{-1} to 9.02 10^{-2} (for Ky reduced by a factor of 5) and from 1.20 10^{-1} to 6.78 10^{-2} (for Ky reduced by a factor of 10).

If the vertical conductivity of the backfill and waste are increased by a factor of 5 and 100, the vertical velocities in the BF and waste are increased, resulting in peak fractional flux values equal to 1.21 10^{-1} and 9.86 10^{-2}, respectively.

3.2 Variation of the Horizontal Conductivity

Waste (W) [Fig. 1(c)]:

As the horizontal hydraulic conductivity (Kx) in the waste is reduced by factors of 5 and 10, the horizontal flow velocity across the waste is reduced, resulting in a decrease in the peak fractional flux from 1.20 10^{-1} to 1.12 10^{-1} and from 1.20 10^{-1} to 1.09 10^{-1}, respectively.

Conversely, increasing the waste horizontal conductivity by factors of 5 and 10 increases the horizontal velocity through the waste, resulting in a peak flux increase from 1.20 10^{-1} to 1.25 10^{-1} for both conductivity factor values.

Upper Vadose (UVZ) [Fig. 1(c)]:

As the upper vadose horizontal hydraulic conductivity is reduced by factors of 5 and 10, the horizontal flow velocity across the upper vadose zone and waste zone is reduced, resulting in a decrease in the peak fractional flux from 1.20 10^{-1} to 1.03 10^{-1} and 1.20 10^{-1} to 9.58 10^{-2}, respectively.

Furthermore, increasing the upper vadose horizontal hydraulic conductivity by factors of 5 and 10 results in higher horizontal flow velocities in the upper vadose zone and waste zone, resulting in an increase in the peak fractional flux from 1.20 10^{-1} to 1.27 10^{-1} for both conductivity factor values.

4 Conclusions

This paper has addressed the sensitivity of I-129 flux in groundwater to the hydraulic conductivities in the vadose zone and the low level waste disposed in trenches. By using the trench configuration and simulation model described in Section 2.0, flow and radionuclide transport analyses results were performed. The results have outlined the relationship between the hydraulic conductivity, the horizontal and vertical flow, and the transport of the radionuclide to the water table. In particular, the results obtained for changes in the hydraulic conductivity have shown:

- the controlling effect of the vertical conductivity of the LVZ on the fractional flux, regardless of the hydraulic conditions of the waste and backfill.

- The inverse relationship of the I-129 fractional flux to changes in the vertical hydraulic conductivity of the UVZ (e.g., increasing the UVZ vertical conductivity decreases the peak flux), because the UVZ provides a competing parallel path for infiltrating water, such that more water can bypass the waste zone. The relationship reverses when the UVZ horizontal conductivity changes; increasing the UVZ horizontal conductivity increases the I-129 peak flux, because more infiltrating water can travel horizontally in the UVZ and enter the sides of the waste zone. A similar relationship holds for the waste; increasing the waste horizontal conductivity increases the I-129 peak flux, because more infiltrating water can enter the sides of the waste zone from the adjoining UVZ.

- Increases in the vertical conductivity of groups of subregions, such as the group (BF+W+UVZ+LVZ),

- decrease the I-129 peak flux; results are mostly affected by increases in the UVZ, because infiltrating

- water can more readily move through the UVZ than through the waste. Such conductivity changes also reduce the effect of the original conductivity anisotropy.

- the negligible effect of the vertical conductivity of the backfill subregion on the flow in the waste and the radionuclide fractional flux.

More generally, the results obtained have demonstrated the importance of the hydraulic conductivity assigned to the materials being modeled, thereby providing valuable insight on the sensitivity of groundwater flow and radionuclide transport to the variations in hydraulic conductivity.

The biggest increases in the I-129 peak fractional flux occurred when (1) the vertical conductivity was increased for the LVZ and (2) the vertical conductivity was decreased for the UVZ. The former case indicates the control of the LVZ for a serial flow path, while the latter case indicates the control of the UVZ for a parallel flow path.

Further results outlining the controlling effect of the flow through the LVZ were obtained when the vertical conductivity was increased for (1) the waste and (2) the waste and backfill. Both increases in vertical conductivity decreased the peak I-129 fluxes. These increases in conductivity forced higher earlier fluxes and earlier peaks, but more rapidly depleted the inventory. With the LVZ flow still controlling, the higher rate of release could not be sustained, producing lower I-129 peak fluxes.

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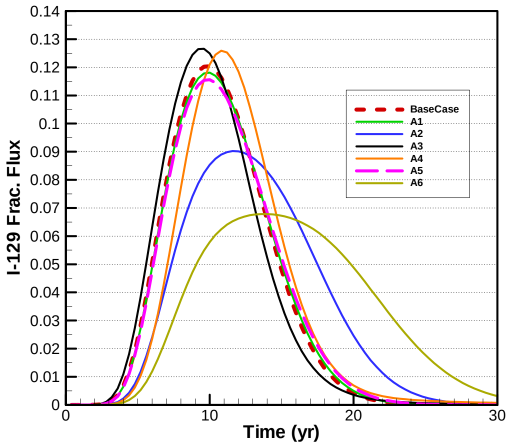
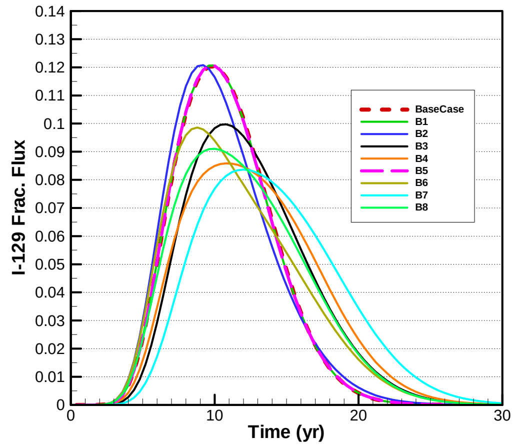
3. Analytic & Computational Research, Inc., 2002. "PORFLOW ™ User's Manual, Version 5, Rev. 5."

Table 2. I-129 Peak Fractional Flux at Water Table relative to Base Case

Case	Peak Time (yr)	Peak Frac. Flux	Ratio to Base Case	Key
Base Case	10	1.20E-01		
A1	10	1.18E-01	9.81E-01	BF/5
A2	11.6	9.02E-02	7.50E-01	(BF+W)/5
A3	9.6	1.27E-01	1.05E+00	(BF+W+UVZ)/5
A4	10.8	1.26E-01	1.05E+00	(BF+W+UVZ+LVZ)/5
A5	10	1.16E-01	9.61E-01	BF/10
A6	13.6	6.78E-02	5.64E-01	(BF+W)/10
B1	10	1.21E-01	1.00E+00	BF*5
B2	9.2	1.21E-01	1.00E+00	(BF+W)*5
B3	10.8	9.98E-02	8.29E-01	(BF+W+UVZ)*5
B4	10.8	8.59E-02	7.14E-01	(BF+W+UVZ+LVZ)*5
B5	9.6	1.21E-01	1.00E+00	BF*100
B6	8.8	9.86E-02	8.19E-01	(BF+W)*100
B7	12	8.37E-02	6.95E-01	(BF+W+UVZ)*100
B8	10	9.11E-02	7.56E-01	(BF+W+UVZ+LVZ)*100
C1	10.8	1.03E-01	8.56E-01	UVZ/5
C2	11.2	9.58E-02	7.96E-01	UVZ/10
C3	9.6	1.27E-01	1.05E+00	UVZ*5
C4	9.6	1.27E-01	1.05E+00	UVZ*10
C5	10	1.12E-01	9.29E-01	W/5
C6	10	1.09E-01	9.04E-01	W/10
C7	10	1.25E-01	1.04E+00	W*5
C8	10	1.25E-01	1.04E+00	W*10
(C cases change Kx, all others change Ky)				
D1	12.4	1.09E-01	9.06E-01	LVZ/10
D2	6.4	1.35E-01	1.12E+00	LVZ*100
D3	14	7.08E-02	5.88E-01	W/10
D4	8.8	1.09E-01	9.07E-01	W*100
E1	8.8	1.33E-01	1.10E+00	UVZ/5
E2	14	6.80E-02	5.65E-01	UVZ*10



(a)



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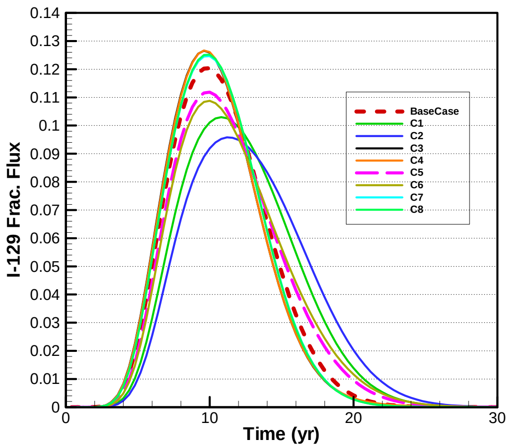

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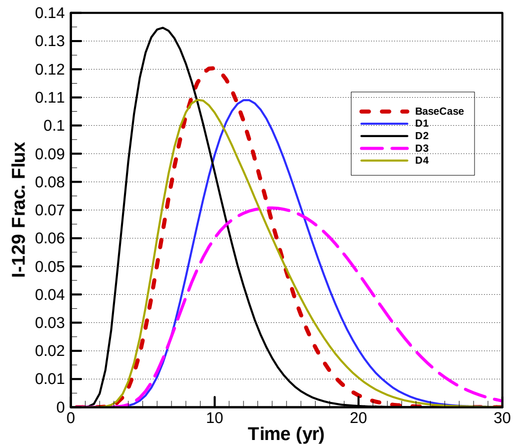

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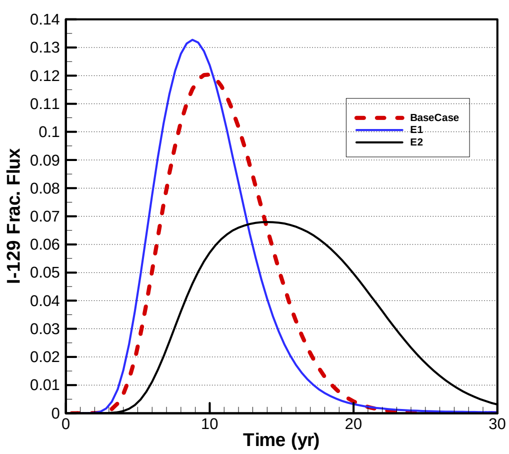

(e)

KEY

A1: BF/5	C1: UVZ/5
A2: (BF+W)/5	C2: UVZ/10
A3: (BF+W+UVZ)/5	C3: UVZ*5
A4: (BF+W+UVZ+LVZ)/5	C4: UVZ*10
A5: BF/10	C5: W/5
A6: (BF+W)/10	C6: W/10
B1: BF*5	C7: W*5
B2: (BF+W)*5	C8: W*10
B3: (BF+W+UVZ)*5	D1: LVZ/10
B4: (BF+W+UVZ+LVZ)*5	D2: LVZ*100
B5: BF*100	D3: W/10
B6: (BF+W)*100	D4: W*100
B7: (BF+W+UVZ)*100	E1: UVZ/5
B8: (BF+W+UVZ+LVZ)*100	E2: UVZ*10

(Note: C cases varied Kx only, all other cases varied Ky only)

Fig. 1. Fractional Flux vs. Time for Vertical and Horizontal Conductivity of Subregions Considered in the Simulation Model